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Using a neural network for qualitative and quantitative predictions of weld integrity in solid bonding dominated processes

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ABSTRACT

Solid-state bonding occurs in several manufacturing processes, as Friction Stir Welding, Porthole Die Extrusion and Roll Bonding. Proper conditions of pressure, temperature, strain and strain rate are needed in order to get effective bonding in the final component. In the paper, a neural network is set up, trained and used to predict the bonding occurrence starting from the results of specific numerical models developed for each process. The Plata–Piwnik criterion was used in order to define a quantitative parameter taking into account the effectiveness of the bonding. Excellent predictive capability of the network is obtained for each process.

1. Introduction

Solid state bonding occurs in different manufacturing processes, as solid state welding processes, e.g. Friction Stir Welding (FSW), Linear Friction Welding (LFW), Rotary Friction Welding (RFW), extrusion of hollow profiles and rolling of multiple sheets. For the mentioned processes, the activation of this phenomenon results in peculiar advantages over more traditional processes. Solid bonding is triggered by proper values of specific field variables at the contact interface between the parts to be joined. The obtained components are usually characterized by better microstructural properties with respect to the parent material.

As far as Friction Stir Welding (FSW) is regarded, it is a relatively new process, patented by TWI in 1991, which can be successfully used to join materials that are difficult-to-weld or unweldeable by traditional fusion welding methods. A key factor to obtain sound joints is the proper choice of the process parameters, which in turn affects the bonding conditions determining the mechanical resistance of the welded joints. FSW is obtained by inserting a specially designed rotating pin into the adjoining edges of the sheets to be welded and then moving it all along the joint [1]. During the process, the tool rotation speed (R) and feed rate (V), determining the heat input into the joint, are combined in a way that an asymmetric metal flow is obtained. In particular, an advancing side and a retreating side are observed: the former being characterized by the "positive" combination of the tool feed rate and of the peripheral tool velocity, the latter having velocity vectors of feed and rotation opposite each other [2]. The material flow observed in the transverse section of a FSW butt joint can be summarized as follows: a material flow coming from the retreating side towards the advancing one is observed; such flow is particularly strong in the upper layers of the blanks due to the action of the tool shoulder. Furthermore, the material is pushed downwards towards the bottom of the joint because of the tilt given to the tool; a change of direction is observed in the material flow and then an ascendant laminar flow in the advancing side is found out. This phenomenon can be enhanced using a conical or threaded pin tool. It should be observed that in the bottom of the joint swirl phenomena may be observed, thus denoting an ineffective material flow and the possible insurgence of internal folding defects due to the geometrical discontinuities introduced by the tool pin shape [3]. The effectiveness of the obtained joint strongly depends on several operating parameters, both geometrical and technological. Proper values of the main field variables, as temperature, strain and strain rate are needed in order to get the final effective bonding [4,5].

Porthole Die Extrusion (PDE) is a process used for the production of hollow profiles: in this process the die determines the external shape of the final component while the mandrel determines its internal shape. During the process, the material separates into two or more seams, in correspondence of the supports of the mandrel, and rejoins in the so-called welding chamber. The solid-state weld then occurs inside the die, producing a complex shape high quality component [6]. Similarly to FSW, sound welds are obtained when proper field variables distributions are obtained as a function of the process specific input parameters, i.e. die geometry, determining the material flow and processing temperature. In the last years some of the authors highlighted similar and

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different aspects in the distributions of temperature, strain, strain rate and pressure of sound parts obtained by FSW and PDE [7].

Solid bonding also occurs in Roll Bonding [8] and Accumulative Roll Bonding (ARB): the latter process was proved effective for significant strengthening and enhancement of microstructural properties of aluminum alloys through grain refinement [9]. For the above processes, again bonding is obtained by properly creating, the needed conditions of material flow, strain, strain rate and temperature.

It is therefore clear how, for a wide range of different techniques, reaching proper solid welding conditions during the process represents a key factor in obtaining sound parts. As explained, the processes input parameters must result in correct distributions of the main field variables and, as a consequence, a detailed knowledge of the processes mechanics is needed. A welding criterion, depending on the local values of the above cited field variables and embedded in a proper process model, represents an important tool for cost effective sound joint design. It is generally accepted that pressure is a crucial factor in determining the mechanical resistance of the joint. A few criteria, mainly related to pressure, temperature and strain, have been proposed by different authors in order to help the die design and predict the effectiveness of the welding process. In the last years, a few research groups worked on the development of a solid bonding criterion for PDE. The first criterion in literature was proposed by Akeret [10] and is based on the ratio between the maximum value of pressure reached and the flow stress of the material during the process. More recently Piwnik and Plata [11] proposed a parameter calculated as the integral in time of the ratio between the contact pressure at the interface of the parts being welded and the material flow stress for the specific process conditions. When the calculated parameter exceeds a predetermined threshold, a sound weld is obtained. Finally, Donati and Tomesani [12] proposed a variation of the previous criterion introducing the nodal velocity to the integral. It is worth noticing that many papers focused on the solid bonding in extrusion have used the Piwnik and Plata criterion as base for their study. In particular, D'Urso et ali[13] developed an integrated experimental and numerical approach based on rolling tests of two different sheets welded together under different temperature and pressure conditions. Different AA6XXX aluminum alloys, i.e. AA6060, AA6061 and AA6082, were used and the threshold value of the Piwnik and Plata criterion was found, through an inverse approach, as a function of temperature. The obtained curves were tested against extrusion experiments demonstrating the effectiveness of the obtained welding limits. However, to the author knowledge, no welding criterion has never been applied to FSW.

In the paper, we present the results of an experimental and numerical campaign on FSW, PDE and RB. In particular, in the second paragraph, the experimental approach utilized to obtain FSWed joints with varying rotational and advancing speed is described. Both sound and not welded joints are produced. Literature data are used for experimental results of PDE and RB. In the third paragraph, the numerical simulations set up is reported for the three processes. In the fourth paragraph, a multilayer feedforward neural network (NN) is set up and the results discussed. The network is able to provide, for each point of observation, a qualitative output indicating the occurrence of solid state welding as well as a quantitative output based on the Piwnik and Plata criterion indicating the level of "soundness" of the weld. The use of a neural network can set free from the limitations of the analytical models, both in terms of range of applicability and of number of experiments needed in order to obtain a qualitative indication on the welding occurrence. In this way, no limiting curve is needed, as it will be better explained in the following. Excellent prediction capabilities are found.

2. Experimental data

2.1. Friction Stir Welding (FSW)

Six different sets of input parameters were used to Friction Stir Weld 2.4 mm thick AA6061-T6 sheets, 60 mm × 100 mm in dimensions, with the aim to highlight different bonding conditions resulting in poor and sound welds. Constant tool plunge and tilt angle were selected with varying tool rotational and welding speed. Experimental details are presented in Table 1.

Fig. 1 shows a weld obtained with process input parameters resulting in a sound joint (Fig. 1a, $R = 1000$ rpm, $v = 100$ mm/s) and a poor weld (Fig. 1b, $R = 500$ rpm, $v = 400$ mm/s). Specimens were cut from each weld to analyze the transverse section of the joint. The specimens were hot mounted, fine grinded and finally etched with Keller reagent for 20 s in order to highlight sound and poorly bonded areas within the same specimen.

2.2. Roll Bonding (RB)

As far as the Roll Bonding process is regarded, experimental data were taken from the paper by D'Urso et al. [13]. In the paper, two sheets were rolled together to a final welded sheet thickness of 10 mm. The tests were carried out with varying initial sheets thickness, in order to obtain different rolling ratio values – ranging from 50% to 83.3% – and sheets temperature – ranging from 300 °C to 530 °C. A chart was built indicating effective bonding and failed tests as a function of temperature and Piwnik and Plata parameter W [11]:

$$W = \int_{t0}^{t1} \frac{p}{\vartheta} dt \qquad (1)$$

Table 1
FSW parameters used for the experimental and numerical campaign.

Parameter	Value
Feed rate V (mm/min)	100, 200, 400
Rotational speed R (rpm)	500, 1000
Tilt angle	2°
Tool plunge (mm)	2.2

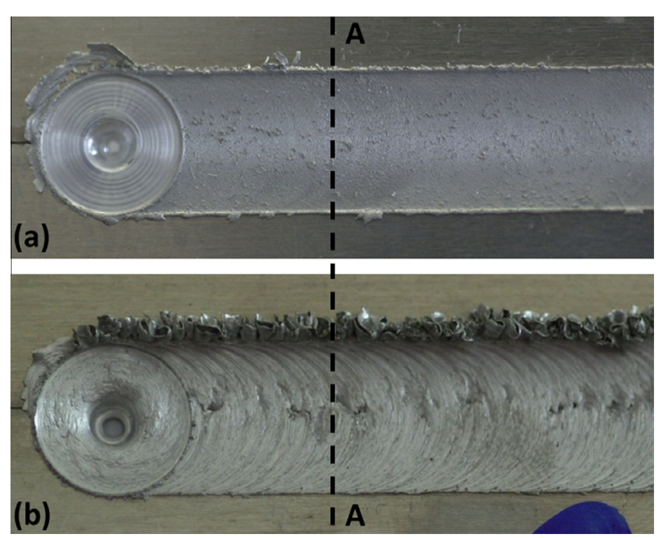

Fig. 1. (a) Sound joint obtained with $R = 1000$ rpm, $v = 100$ mm/s and (b) poor joint obtained with, $R = 500$ rpm, $v = 400$ mm/s.